

Revisiting 802.11 for User Fairness and Efficient Channel Utilization in Presence of LTE-U

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Abstract—A promising solution satisfying the industry’s demand to have minimum alterations in LTE for its operation in unlicensed spectrum is duty cycled LTE-U scheme, which adopts discontinuous transmission to ensure fair coexistence with 802.11 (Wi-Fi) WLANs. Even though the scheme guarantees to maintain Wi-Fi network performance, the fairness among Wi-Fi users still remains arcane. In this work, we present a practical scenario where LTE-U, despite being discontinuous (by following an ON/OFF cycle), results in not only unfair throughput distribution among Wi-Fi users but also causes degradation in Wi-Fi APs downlink performance. This is due to the domination of few Wi-Fi users who harness channel in both ON and OFF durations of LTE-U, namely non-victim users over those who get access only in OFF duration, called victim users. In this paper, we studied the performance of victim and non-victim Wi-Fi users, and Wi-Fi AP while varying LTE-U ON duration (*i.e.*, duty cycle). A propitious scheme is proposed for WLANs, with regard to ease of implementation, employing Point Coordination Function (PCF) mode of 802.11, promising fairness among Wi-Fi users with improvement in the channel utilization of Wi-Fi network. An analytical model is developed to demonstrate guaranteed improvement and validate the simulation results.

I. INTRODUCTION

An incessant increase in cellular data traffic demand has called upon the traditional telecom operators, to focus on the unlicensed spectrum as a promising solution [1], [2]. Fair coexistence with other technologies operating in unlicensed spectrum—mainly 802.11 (Wi-Fi)—needs to be ensured for successful deployment of LTE-U in different regulatory domains. Though the two schemes, LTE-U Listen Before Talk (LBT) and duty cycled LTE-U are shown to be equally fair with Wi-Fi [3], the need for quick deployment has forced LTE-U forum [1] to narrow its focus on markets promoting duty cycled LTE-U. Duty cycled LTE-U is a simple scheme where LTE-U eNB follows duty cycle based discontinuous transmission approach to fairly share an unlicensed channel with Wi-Fi networks operating on the same channel. One such example is Carrier Sense Adaptive Transmission (CSAT) [4], where LTE-U eNB follows ON and OFF cycle pattern in a given duty cycle period, with ON duration corresponding to LTE-U transmission duration meant to serve LTE-U users in downlink (LTE-U uses unlicensed spectrum only to serve in downlink [1]) and OFF duration corresponding to LTE-U no-transmission duration, to allow Wi-Fi operation. This works well until Wi-Fi AP, the center of communication in an infrastructure Basic Service Set (BSS), is also affected by LTE-U transmissions and hence can serve its users only in

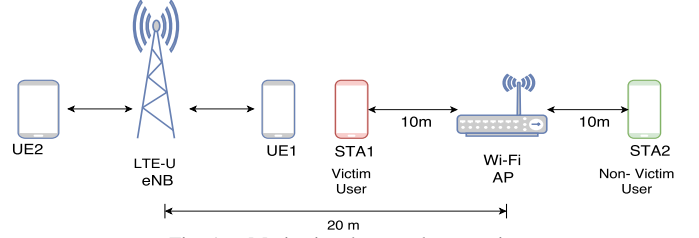


Fig. 1. Motivational example scenario.

LTE-U OFF duration. But in a scenario, where Wi-Fi AP and some users can transmit or receive packets in LTE-U duty cycle (*i.e.*, LTE-U ON period), while remaining users cannot transmit or receive, channel access and consequently the throughput among Wi-Fi users becomes unfair. A similar scenario is considered in [5] where they presented an intercell interference coordination technique when two LTE-U eNBs interfere, but managing a scenario when LTE-U eNB interferes with some users of a Wi-Fi network is unprecedented and is considered as a part of our study in this paper.

Fig. 1 shows a scenario where the effect of LTE-U on Wi-Fi AP is not to an extent that Wi-Fi AP has to defer from channel access during the LTE-U ON period, implying that it can operate in both the LTE-U ON and OFF periods. A Wi-Fi network following Distributed Coordination Function (DCF) mode of operation (referred as standard Wi-Fi for rest of the paper) ensures that every Wi-Fi user has equal chance to access the channel, including the Wi-Fi AP—which is what happens when LTE-U is in OFF period. But when LTE-U is in ON period, Wi-Fi users affected by LTE-U, fail to successfully transmit or receive any data due to two reasons. First, because they sense channel busy due to LTE-U transmissions and second, the interference from LTE-U decreases their Signal to Interference plus Noise Ratio ($SINR$), below a minimum $SINR$ required for successful transmission. Note that the successful transmissions in a Wi-Fi network are only the ones which are successfully received and acknowledged, failure to receive a packet or even acknowledge a successfully received packet would eventually be considered as an unsuccessful transmission. We call these users as victim users. On the other hand, remaining users, called as non-victim users, continue to transmit and receive, even during the LTE-U ON period and thus dominate the victim users. In Fig. 1, STA1 is a victim user while STA2 is a non-victim user. This domination of non-victim users during the LTE-U ON period causes severe unfairness among the victim and non-victim users.

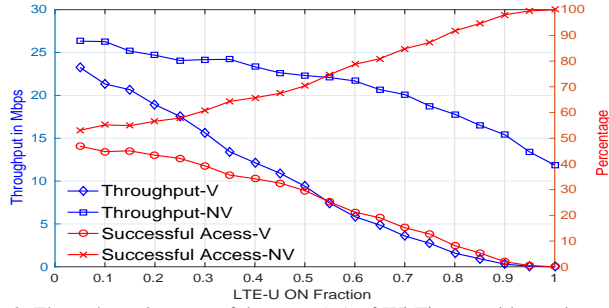


Fig. 2. Throughput & successful access (%) of Wi-Fi user with varying η .

Also, every attempt of transmission from Wi-Fi AP to the victim users, during the LTE-U ON period fails and thus elicits multiple retransmissions of the same packet, wasting the channel resources extensively. Hence, our focus in this work, mainly lies in improving the fairness and channel utilization in the above scenarios by enhancing the throughput of victim users and Wi-Fi AP irrespective of LTE-U duty cycle.

II. MOTIVATIONAL EXAMPLE

To study fairness and channel utilization of Wi-Fi in presence of LTE-U, we consider a scenario with an LTE-U eNB and a Wi-Fi AP deployed 20m apart, each with two users as shown in Fig. 1. STA1 and STA2 are two Wi-Fi users with STA1 being a victim user because the interference from LTE-U causes its $SINR$ to decrease below a minimum required $SINR$ in LTE-U ON period while STA2 is a non-victim user. We considered a full buffer case for Wi-Fi network, where all Wi-Fi users and the Wi-Fi AP always have data to transmit in UpLink (UL) and DownLink (DL), respectively. For LTE-U network, a similar full buffer case is assumed where unlicensed spectrum is used only for sending DL traffic. LTE-U uses a centralized scheduler while Wi-Fi follows DCF mechanism at MAC layer for sharing radio resources.

If LTE-U detects the presence of a Wi-Fi user (by periodically listening to the channel), LTE-U inherently follows an ON-OFF duty cycle [1], [4]. We varied the fraction of time LTE-U is ON in a duty cycle period, LTE-U ON fraction (η) from 0 to 1 and observed the performance of Wi-Fi users, namely the victim and non-victim users. Key observations from our study are:

1) *Disproportionate throughput and successful channel access among victim and non-victim users:* Fig. 2 shows variation of successful channel access percentage (defined as the ratio of successful attempts of transmitting or receiving data by a user to the total successful attempts by all users in the network) and throughput for each user with η . It can be observed that the victim user (STA1) has an inevitably less successful access percentage and throughput as compared to the non-victim user (STA2). In principle, LTE-U ceases to access the channel, during its OFF cycle, so that the victim users not only get channel access but also transmit and receive their packets satisfying minimum $SINR$ requirement. Non-victim users access to the channel—during this (LTE-U OFF) period—engenders unequal, sometimes very low successful channel access and throughput for the victim users.

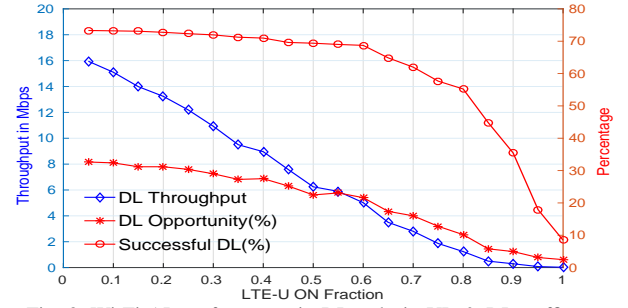


Fig. 3. Wi-Fi AP performance in DL only in UL & DL traffic.

2) *High retransmission loss because of victim users:* Packets from the Wi-Fi AP to victim user (STA1) cannot be successfully received, during the LTE-U ON period, due to their low $SINR$. This results in retransmission of same packet to the same victim user multiple times, with every retransmission increasing the Contention Window (CW) exponentially, resulting an increase in average Back Off (BO) value of Wi-Fi AP. This increase reduces the channel access opportunity of the Wi-Fi AP. Fig. 3 shows a significant decrease in the DL opportunity percentage (defined as the ratio of Wi-Fi AP DL access opportunities to the total access opportunities in Wi-Fi network) and successful DL percentage (defined as the ratio of successful DL transmissions to the total DL transmissions by AP) with increase in η . Fig. 3 also shows a decrease in DL throughput of Wi-Fi AP, which is a result of decreased DL access opportunities and successful DL transmissions.

III. SYSTEM MODEL

We consider a scenario where LTE-U eNB and Wi-Fi AP from same or different operators coexist on the same unlicensed channel with the same amount of bandwidth. The users are associated with either LTE-U or Wi-Fi, with LTE-U following a duty cycle based scheme for fair coexistence with Wi-Fi. The fraction of time LTE-U uses for transmission (η) in duty cycle period can be fixed or adaptively adjusted depending on Wi-Fi channel utilization [1], [4]. To make proper and efficient use of unlicensed spectrum, it is important to have some kind of (indirect) coordination between LTE-U and Wi-Fi AP devices. Hence, we assume that there is an inter-RAT controller as in [6], [7]. The inter-RAT controller can be implemented by the operator if both LTE-U and Wi-Fi AP are deployed by the same operator or it can be implemented by a third party vendor to extend the service among different operators. The controller communicates with LTE-U eNB and Wi-Fi AP to synchronize the LTE-U duty cycle period with the Wi-Fi beacon interval (in multi-eNBs and multi-APs scenario, the controller will synchronize all the Wi-Fi APs to a single beacon interval, and all the LTE-U eNBs also to the same beacon interval). Beacons in Wi-Fi are the management frames, sent by the Wi-Fi AP periodically, containing the network information, and beacon interval is the frequency at which these beacons are sent. After synchronization, if AP changes the beacon interval, it will re-advertise the beacon transmission time and the beacon interval to LTE-eNB via

the controller. Now it is made as the responsibility of eNB to match its duty cycle period to the beacon interval (i.e., LTE OFF time + LTE ON time = beacon interval) and always start the OFF period at the beginning of new beacon interval. LTE-U eNB also informs the fraction of time it is ON (η) to the AP via the controller and allows Wi-Fi AP to improve channel utilization. Fig. 4 shows the considered

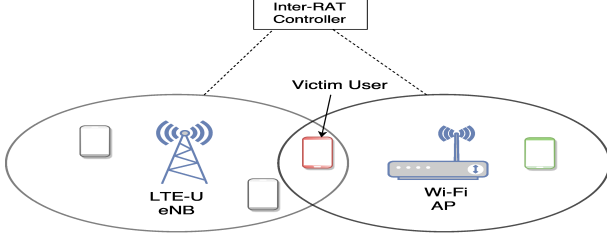


Fig. 4. System model.

system model where LTE-U cell and Wi-Fi BSS are partially overlapped. Workflow of the system model is as follows: Wi-Fi user informs to the AP whenever it detects any non Wi-Fi signal (with its capability to differentiate Wi-Fi and non-Wi-Fi signals using Wi-Fi preamble) causing interference to an extent that its minimum SINR requirement is not satisfied to establish communication. Whenever Wi-Fi AP has a victim user, the AP reports to the inter-RAT controller and starts following a co-ordination approach. Cellular users are not considered as victim users because LTE eNB can serve them using the licensed spectrum whereas Wi-Fi AP has only unlicensed spectrum to serve its users.

IV. PROPOSED WORK

Observations from the motivational example persuades one, for a need to adopt a scheme to ensure the fairness among Wi-Fi users. The DCF mechanism during both the LTE-U ON and OFF durations, without any intelligent steps to improve the network performance—despite having throughput knowledge of the users—can be identified as the main bottleneck. Our work identifies this bottleneck, and then proposes an intelligent and controlled use of Point Coordination Function (PCF) mechanism, without much modification to the existing system, to address this issue and thereby harnesses maximum gain.

A. Use of Point Coordination Function

The scenario presented in the above system model, requires a control in the channel access of non-victim users accompanied by a special channel access given to the victim users. To accomplish the above goal, we advocate usage of PCF mode of Wi-Fi, where the channel is divided into two periods—Contention Free Period (CFP) and Contention Period (CP)—with the difference being that the CP involves contention among users whereas CFP requires only those users to be served which are polled or selected by the Wi-Fi AP. Since, victim users cannot be served in the LTE-U ON period, our proposed scheme allows the Wi-Fi AP to transmit and receive data from victim users during the LTE-U OFF period—by using CFP. After the victim users are served, for the remaining

LTE-U OFF period, AP follows CP (i.e., DCF) to serve all the users, with each user contending and gaining access to the medium. With the onset of LTE-U ON period, Wi-Fi network still continues to be in CP, but Wi-Fi AP having the additional knowledge of victim users, does not attempt to serve the victim users. This prevents unnecessary re-transmissions and helps the Wi-Fi AP, maintain its channel access opportunity same as non-victim users. The complete operation is illustrated in Fig. 5. Also, we propose that the Wi-Fi AP sends its beacons at the beginning of LTE-U OFF period. This ensures that every Wi-Fi user listens to them, which is important for a user to maintain its association with the Wi-Fi network.

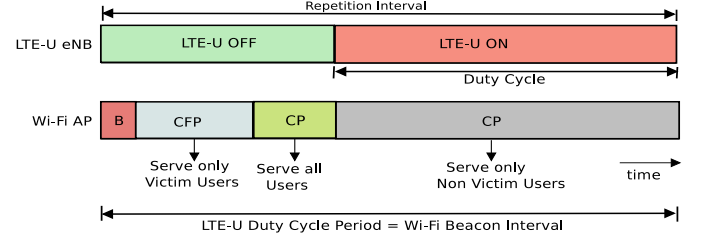


Fig. 5. Use of PCF mode for victim users.

B. Optimum value of CFP

If the entire LTE-U OFF period was used to serve the victim users (by making entire LTE-U OFF duration as CFP), the result can be, victim users gaining undue advantage in terms of throughput. To avoid this, we find the minimum CFP duration, within the LTE-U OFF period, that is required for ensuring throughput fairness among the Wi-Fi users. If x is the duration to operate in CFP, variation in x can give control of how much the victim users has perquisite over the non-victim. In the case when x is made as zero, the proposed scheme degenerates to standard Wi-Fi. Any value of x between 0 to η will give better throughput for the victim users (if present) as well for the entire Wi-Fi setup. One approach to realize optimum CFP duration is to adjust x by observing the throughputs of previous duty cycle period. The updated CFP duration (T_{cfp}) in terms of previous CFP duration T_{cfp}^{old} can be given as

$$T_{cfp} = \frac{\Gamma_{nv}^{new}}{\Gamma_v^{new}} * T_{cfp}^{old} \quad (1)$$

Γ_{nv}^{new} and Γ_v^{new} are calculated using average throughputs of non-victim and victim users, respectively as

$$\Gamma_{nv}^{new} = (1 - \alpha) * \Gamma_{nv}^{prev} + \alpha * \Gamma_{nv}^{old} \quad (2)$$

$$\Gamma_v^{new} = (1 - \alpha) * \Gamma_v^{prev} + \alpha * \Gamma_v^{old} \quad (3)$$

Where Γ_{nv}^{prev} and Γ_v^{prev} are average throughputs in previous duty cycle period and Γ_{nv}^{old} and Γ_v^{old} are the Γ_{nv}^{new} and Γ_v^{new} of the previous duty cycle period, for non-victim and victim user, respectively and α is a smoothing parameter.

V. THROUGHPUT ANALYSIS OF PROPOSED SCHEME

For analyzing throughput of proposed scheme, we consider an LTE-U eNB and a Wi-Fi AP, each having N_t clients. Wi-Fi throughput with PCF mode enabled (proposed scheme) differs

extensively from its standard mode of operation (*i.e.*, a Wi-Fi network with nodes configured in DCF mode). We compare the throughput of proposed scheme with that of the standard Wi-Fi operation. LTE-U is assumed to serve its unlicensed users in DL [2], and Wi-Fi is studied for the following two scenarios:

- 1) DL only traffic from the AP to its users.
- 2) UL and DL traffic at all nodes in the network.

A. DL only traffic with full buffer

Let T_{difs} , T_{slot} , and T_{sifs} denote the DIFS interval, back-off slot time, and SIFS interval for the Wi-Fi network, respectively. Let T_{busy} denote the amount of time channel will be busy after a data transmission start. Therefore, $T_{busy} = T_{rts} + T_{sifs} + T_{cts} + T_{sifs} + T_{data} + T_{sifs} + T_{ack}$, where T_{data} represents the average time required to successfully transmit a data packet - when LTE-U is ON and T_{ack} represents the average time required to transmit an ACK. Let Q_K denote the random back-off value selected by the Wi-Fi AP during the K^{th} transmission and T_{succ} denotes the average time taken by the AP to transmit one data burst successfully. Since a DL only traffic will not elicit any collisions, $P(Q_K = q_k) = \frac{1}{W}$, where W denotes the minimum back-off window size and average value of q_k is given as $E[q_k] = \frac{W-1}{2}$ then T_{succ} is given by

$$\begin{aligned} T_{succ} &= E[T_{difs} + T_{slot} * q_k + T_{busy}] \\ &= T_{difs} + \frac{W-1}{2} * T_{slot} + T_{busy} \end{aligned} \quad (4)$$

To determine the throughput of such scenario, we employ slot based approach, which assumes that Wi-Fi AP follows a process of transmitting the data on a per slot basis. A slot in essence, is determined by the time it takes to transmit to a victim or a non-victim user.

During the LTE-ON period, successful transmission to a victim user is indeed not possible (due to low SINR). So the Wi-Fi AP will keep on sending Request-to-Send (RTS) packets, until the number of attempts reaches the Short Retry Limit (R_{limit}), before it discards the packet. Nonetheless, a non-victim user can be served successfully during this period (assuming an ideal channel). Therefore, on an average a successful transmission will last for T_{succ} and an unsuccessful, involving Clear-to-Send (CTS) time out duration ($T_{cts_timeout}$), R_{limit} number of re-transmissions and exponential growth of CW with every re-transmission, will last for $T_{un-succ}$, where

$$T_{un-succ} = \frac{1}{2} \left[2^m W (R_{limit} - m + 1) - R_{limit} - W \right] + R_{limit} (T_{difs} + T_{rts} + T_{cts_timeOut}) \quad (5)$$

and, m denotes $\log_2 \frac{CW_{max}}{W}$. Let T_i be a random variable representing the time consumed by any slot, given by

$$T_i = \begin{cases} T_{un-succ} & \text{with prob. } p \\ T_{succ} & \text{with prob. } 1-p \end{cases} \quad (6)$$

$$\text{and } E[T_i] = p * T_{un-succ} + (1-p) * T_{succ} \quad (7)$$

where $p = \frac{N_v}{N_t}$, assuming that AP randomly selects a user to serve, with no special preferences.

The total time taken by n such slots will be given by

$$T = \sum_{i=1}^n T_i \implies E[T] = E\left[\sum_{i=1}^n T_i\right] = \sum_{i=1}^n E[T_i]$$

Since, T_i 's are Independent and Identically Distributed (IID) copies of each other,

$$E[T] = n * E[T_i] \quad (8)$$

Using T_{succ} and $T_{un-succ}$, we categorize the performance of standard Wi-Fi and proposed scheme to show the benefits in terms of fairness achieved among Wi-Fi users and throughput improvement in Wi-Fi network.

1) *Standard Wi-Fi*: Since the behavior of Wi-Fi during the LTE-ON and LTE-OFF periods is quite dissimilar, we analyze both of them separately. During the LTE-OFF period, all the Wi-Fi transmissions are successful, implying that there is no randomness involved in the slot duration (T_i).

$$T_i = T'_{succ} \quad \text{and} \quad E[T] = n * T'_{succ}$$

T'_{succ} differs from T_{succ} in T_{data} ; no interference from LTE-U causes Wi-Fi AP to use higher Modulation and Coding Scheme (MCS) and thus will decrease T_{data} , and $T'_{succ} < T_{succ}$. If average size of packet is $E[P]$ (bytes), then the total number of bytes transmitted during this interval will be $n * E[P]$ and the throughput of network during the LTE-OFF period (Γ_{off}^S) will be

$$\Gamma_{off}^S = \frac{n * E[P]}{n * T'_{succ}} = \frac{E[P]}{T'_{succ}} \quad (9)$$

The victim user ($\Gamma_{off,v}^S$) and non-victim user ($\Gamma_{off,nv}^S$) throughputs will be same and are given by

$$\Gamma_{off,v}^S = \Gamma_{off,nv}^S = \frac{\Gamma_{off}^S}{N_t} = \frac{1}{N_t} * \frac{E[P]}{T'_{succ}} \quad (10)$$

During the LTE-ON period, AP will be able to successfully transmit to a non-victim user, but its transmission to a victim user, will be unsuccessful. This will cause T_i to be a random variable, fluctuating between T_{succ} and $T_{un-succ}$, given by Eqn (4) and Eqn (5). The average duration to complete n transmissions ($E[T]$) during this interval is given by

$$E[T] = nE[T_i] = n(pT_{un-succ} + (1-p)T_{succ}) \quad (11)$$

Data packet is transmitted only when a successful transmission takes place, *i.e.*, if the packet is meant for a non-victim user, implying that the average amount of data successfully transmitted is the sum of all transmissions to the non-victim users in the Wi-Fi network. Therefore, the average amount of data transmitted is $n(1-p)E[P]$. The total throughput Γ_{on}^S can then be given by

$$\Gamma_{on}^S = \frac{(1-p)E[P]}{(pT_{un-succ} + (1-p)T_{succ})} \quad (12)$$

Since the victim users do not receive any data, their throughputs ($\Gamma_{on,v}^S$) will be zero ($\Gamma_{on,v}^S = 0$), while the non-victim users will equally share the total throughput as

$$\Gamma_{on,nv}^S = \frac{1}{N_t - N_v} \frac{(1-p)E[P]}{(pT_{un-succ} + (1-p)T_{succ})} \quad (13)$$

The total throughput of a victim user (Γ_v^S) and that of a non-victim user (Γ_{nv}^S) in a duty cycle period are given by

$$\Gamma_v^S = (\eta)\Gamma_{on,v}^S + (1-\eta)\Gamma_{off,v}^S = (1-\eta)\frac{1}{N_t} * \frac{E[P]}{T'_{succ}} \quad (14)$$

$$\text{Similarly, } \Gamma_{nv}^S = (\eta)\Gamma_{on,nv}^S + (1-\eta)\frac{1}{N_t} * \frac{E[P]}{T'_{succ}} \quad (15)$$

Hence, the total Wi-Fi throughput (Γ^S) of standard Wi-Fi network in the presence of LTE-U is

$$\begin{aligned} \Gamma^S &= (N_v)\Gamma_v^S + (N_t - N_v)\Gamma_{nv}^S \\ &= (\eta)(N_t - N_v)(\Gamma_{on,nv}^S) + \left((1-\eta)\frac{E[P]}{T'_{succ}}\right) \end{aligned} \quad (16)$$

2) *Proposed scheme:* Using the information, regarding the presence of victim users and LTE-U ON period, in our proposed scheme (for efficient utilization of unlicensed spectrum) the Wi-Fi AP intelligently defers from transmitting to the victim users during LTE-U ON period, and serves these users using PCF mode during LTE-U OFF period. Since LTE-ON period involves only the non-victim users transmissions, every transmission will be successful and will last for T_{succ} duration. Hence, the throughput of each non-victim ($\Gamma_{on,nv}^{PS}$) and victim ($\Gamma_{on,v}^{PS}$) user is given by

$$\Gamma_{on,v}^{PS} = 0 \quad \text{and} \quad \Gamma_{on,nv}^{PS} = \frac{1}{N_t - N_v} * \frac{E[P]}{T_{succ}} \quad (17)$$

But, during the LTE-OFF period, the behavior of proposed scheme is quite ingenious. Let T_{cfp} denote the average time taken to serve a victim user, in LTE-OFF period using CFP. The time taken to transmit a data packet (and receive an ACK) using CFP is given by

$$T_{cfp} = T_{sifs} + T_{data} + T_{sifs} + T_{ack} \quad (18)$$

Assuming average size of packet as $E[P]$, time taken for n such transmissions (T_{cfp}^n) and throughput of total network (Γ_{off}^{cfp}) are given by

$$T_{cfp}^n = \sum_{i=1}^n T_{cfp} = n * T_{cfp} \quad \text{and} \quad \Gamma_{off}^{cfp} = \frac{E[P]}{T_{cfp}} \quad (19)$$

As none of the non-victim users are being served in the CFP, their throughput ($\Gamma_{off,nv}^{cfp}$) will be zero, while the victim users ($\Gamma_{off,v}^{cfp}$) equally share the total throughput as

$$\Gamma_{off,nv}^{cfp} = 0 \quad \text{and} \quad \Gamma_{off,v}^{cfp} = \frac{1}{N_v} * \frac{E[P]}{T_{cfp}} \quad (20)$$

With the remaining time in which the LTE is still OFF, Wi-Fi uses PCF mode in CP to serve all the users, which will have

the throughput, same as that of standard Wi-Fi operating in LTE-OFF period (Γ_{off}^S). Hence, the Wi-Fi throughput during the LTE-OFF period within CP (Γ_{off}^{cp}) is given as

$$\Gamma_{off}^{cp} = \Gamma_{off}^S \quad (21)$$

Also, each victim ($\Gamma_{off,v}^{cp}$) and non-victim user ($\Gamma_{off,nv}^{cp}$) will have equal throughputs as

$$\Gamma_{off,v}^{cp} = \Gamma_{off,nv}^{cp} = \frac{\Gamma_{off}^S}{N_t} \quad (22)$$

Assuming that the fraction of time, Wi-Fi operates in CP, during the LTE-U OFF period, as $x \leq (1-\eta)$, the total average throughput of each victim (Γ_v^{PS}) and non-victim user (Γ_{nv}^{PS}), with the proposed scheme can be given as

$$\begin{aligned} \Gamma_v^{PS} &= (\eta)\Gamma_{on,v}^{PS} + (1-\eta-x)\Gamma_{off,v}^{cp} + (x)\Gamma_{off,v}^{cfp} \\ &= (1-\eta-x)\frac{1}{N_t} \frac{E[P]}{T'_{succ}} + (x)\frac{1}{N_v} \frac{E[P]}{T_{cfp}} \end{aligned} \quad (23)$$

Similarly,

$$\begin{aligned} \Gamma_{nv}^{PS} &= (\eta)\Gamma_{on,nv}^{PS} + (1-\eta-x)\Gamma_{off,nv}^{cp} + (x)\Gamma_{off,nv}^{cfp} \\ &= (\eta)\frac{1}{N_t - N_v} \frac{E[P]}{T_{succ}} + (1-\eta-x)\frac{1}{N_t} \frac{E[P]}{T'_{succ}} \end{aligned} \quad (24)$$

Hence, the total Wi-Fi throughput (Γ^{PS}) in our proposed scheme is given by

$$\begin{aligned} \Gamma^{PS} &= (N_v)\Gamma_v^{PS} + (N_t - N_v)\Gamma_{nv}^{PS} \\ &= (\eta)\frac{E[P]}{T_{succ}} + (1-\eta-x)\frac{E[P]}{T'_{succ}} + (x)\frac{E[P]}{T_{cfp}} \end{aligned} \quad (25)$$

3) *Observations and gains:* (i) *Throughput of each victim user will increase irrespective of η :* Using Eqn (14) and Eqn (23), Γ_v^{PS} can be re-written as

$$\Gamma_v^{PS} = \Gamma_v^S + (x)\left(\frac{E[P]}{N_v * T_{cfp}} - \frac{E[P]}{N_t * T'_{succ}}\right) \quad (26)$$

The second term on the Right Hand Side (RHS) of Eqn (26) indicates whether the proposed scheme can outperform standard Wi-Fi in terms of throughput of victim user. The two fractions within the second term are the throughputs of victim user in the x duration with the proposed scheme and standard Wi-Fi, respectively.

Since, $T_{cfp} < T'_{succ}$ and $N_v \leq N_t$,

$$\frac{1}{N_v} \frac{E[P]}{T_{cfp}} > \frac{1}{N_t} \frac{E[P]}{T'_{succ}} \implies \Gamma_v^{PS} > \Gamma_v^S \quad (27)$$

(ii) *Total throughput of Wi-Fi network will increase regardless of η :* Using Eqns (16) and (25), Γ^{PS} can be written as

$$\begin{aligned} \Gamma^{PS} &= \Gamma^S + x\left(\frac{E[P]}{T_{cfp}} - \frac{E[P]}{T'_{succ}}\right) + \\ &\quad \eta\left(\frac{E[P]}{T_{succ}} - \frac{E[P]}{\left(\frac{p}{1-p}T_{un-succ} + T_{succ}\right)}\right) \end{aligned} \quad (28)$$

Since, $T_{un-succ} > 0$ and $T'_{succ} > T_{cfp}$, implies that all the terms on the RHS are positive. Therefore, $\Gamma^{PS} > \Gamma^S$.

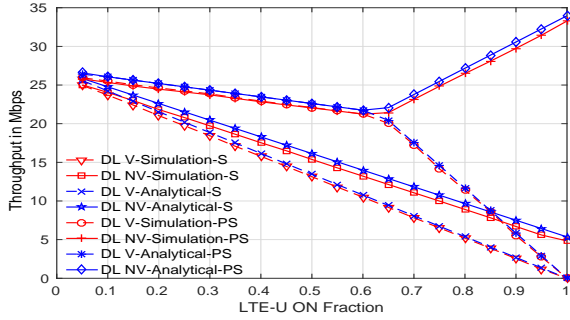


Fig. 6. Throughput of both the schemes in DL only traffic with varying η .

B. UL and DL full buffer scenario

Here, we assume that all the Wi-Fi nodes including the AP are saturated. Achieving fairness among Wi-Fi users becomes much more challenging—with non-victim users transmitting huge amount of data in UL. During the LTE-ON period, the Wi-Fi AP as well as the victim users will increase their CWs, due to mutual packet loss, whereas, the non-victim users will maintain a reasonable CW size and hence, access the medium very frequently. Since most of these accesses are successful (except for those which collide), their UL throughput will drastically increase, resulting in further unfairness. The network throughput might seem to be reasonable, but the DL throughput can reach a very low value (due to the increase in Wi-Fi AP's CW), which is unpalatable in many scenarios. Using the proposed scheme, Wi-Fi AP defers from transmitting to victim users during LTE-U ON period, implying that its CW remains similar to that of non-victim users and hence, UL and DL throughputs remain evenly distributed.

During the LTE-U OFF period, the proposed scheme would increase the throughput of victim users, similar to the DL only scenario, with Wi-Fi AP sending and receiving data from victim users in CFP. An optimum value of the CFP duration will be reached and in each duty cycle period, the throughputs of victim and non-victim users would become identical. Further, a good uniformity between the UL and DL traffic would be achieved in the network.

VI. PERFORMANCE EVALUATION

The system model described in Section III has been simulated using MATLAB with parameters given in Table I. For simulation, we considered the same scenario as shown in Fig. 1. Results with standard Wi-Fi are compared with the proposed scheme by simulating for 10 seconds and averaging over 10 different seed values. As the focus is to improve performance of victim users and Wi-Fi network, irrespective of duty cycle, the results are shown for the same.

A. DL traffic with full buffer

Fig. 6 shows the throughputs of victim and non-victim user with the proposed scheme (PS) and Standard Wi-Fi (S) in DL only scenario. The figure has both simulation and analytical plots for varying η . It shows that the throughputs of victim and non-victim user are not just higher (compared to standard Wi-Fi) but also are identical, thereby achieving fairness among Wi-Fi users, all the way from $\eta = 0$ (LTE-U completely OFF)

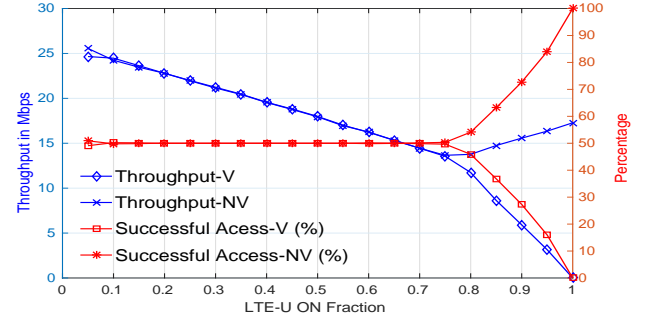


Fig. 7. Throughput and access(%) of proposed scheme in UL & DL traffic.

TABLE I
Wi-Fi & LTE-U PARAMETERS

Wi-Fi parameters		Common Parameters	
Parameters	Values	Parameter	Value
CW_{min}, CW_{max}	16,1024	Tx Power	20 dBm
PHY, MAC Header	128,272 bits	Operating Freq.	5.3 GHz
ACK,RTS	240,288 bits	Noise	-101 dBm
Payload,MPDU	8148 bits,4	Bandwidth	20 MHz
Slottime,CTStimeout	9,50 μ s	Antenna Ht.	10 meter
DIFS, SIFS	34,16 μ s	User Antenna Ht.	1 meter
Beacon Interval, α	100 ms,0.5	Antenna	SISO
Parameter		Value	
Wi-Fi PHY Rates (Mbps)	6.5 13, 26, 39, 52, 78, 104, 117, 130		
Required SNR (in dB)	2, 5, 7, 9, 13, 17, 20, 22, 23		
Traffic	Full buffer via saturated UDP flows		
Channel	No shadow/Rayleigh fading		
Path Loss Model [8]	36.7log10(d[m])+22.7+26log10(freq[GHz])		

to $\eta < \eta_t$. We define η_t as the maximum value of η for which throughput fairness is achievable. For $\eta > \eta_t$, the LTE-U OFF duration (i.e., $1 - \eta$) is insufficient to provide the victim user with same throughput as that of the non-victim user, in spite of configuring the complete LTE-U OFF period as CFP.

Improvement in victim users throughput can be attributed to the use of CFP by the Wi-Fi AP to serve them, and improvement in non-victim users throughput can be imputed to the fact that Wi-Fi AP does not waste the channel in transmitting to the victim users during the LTE-ON duration and serves only the non-victim users. This further helps the network to maintain throughput, especially in scenarios where $\eta > \eta_t$. From both simulation and analytical results, it is clearly conveyed that our proposed scheme performs better in achieving fairness for $\eta \leq \eta_t$, and improving channel utilization as compared to the standard Wi-Fi, irrespective of η .

B. UL and DL traffic with full buffer

Figs. 2 and 7 show the performance of victim and non-victim users—in terms of their throughputs and successful channel access percentages with varying η —for standard Wi-Fi and proposed scheme, respectively. A similar trend in throughput, as with DL only traffic, can be observed ensuring fairness among the victim and non-victim users for $\eta \leq \eta_t$, (with $\eta_t = 0.75$). For $\eta > \eta_t$, the above conclusion, of LTE-U OFF period being insufficient for victim user still holds true. Successful channel access also being equal confirms that the throughput fairness was a result of equal access. Apart from fairness, for all $\eta < 1$, a noticeable improvement in the throughput of victim user can be observed.

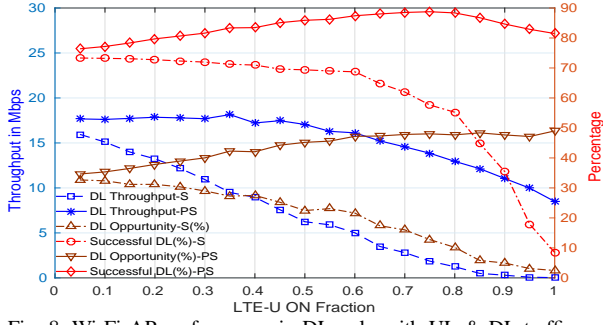


Fig. 8. Wi-Fi AP performance in DL only with UL & DL traffic.

Fig. 8 shows the performance of Wi-Fi AP in terms of DL throughput, DL opportunity, and successful DL transmission by varying LTE-U ON fraction. DL opportunity in case of standard Wi-Fi (also shown in Fig. 3) decreases as η increases, since multiple retransmissions to victim user increases the average BO value. While, with the proposed scheme, the Wi-Fi AP cleverly defers from transmitting to the victim user, during LTE-U ON period and avoids unnecessary increase in its average BO value, thereby preventing the decrease in DL opportunity of Wi-Fi AP. DL opportunity is now expected to be at 33% when η is 0 (since all the three nodes get equal chance to access the channel, when LTE-U is OFF), and would increase to 50% when η is 1. A DL opportunity of 50% (at $\eta = 1$) signifies that the non-victim user does not dominate the network and Wi-Fi AP still obtain equal chance to transmit as compared to the non-victim user.

Successful DL percentage in Fig. 8, which in the standard Wi-Fi was highly impacted by the retransmissions to the victim user, is now—with the proposed scheme—just influenced by the collisions in the network, and hence is very high. Successful DL percentage increases with η until η_t . An increase in LTE-U ON time demands for more CFP (to achieve fairness), and higher the CFP duration in a duty cycle, lower the collisions and hence Successful DL percentage increases with η . For $\eta > \eta_t$, CFP duration is limited by LTE-U OFF time. Increasing η more than η_t , will decrease the CFP duration due to a decrease in LTE-U OFF period. This constrained decrease in CFP duration results in a slight decrease in Successful DL percentage (for $\eta > \eta_t$). Further, the DL throughput of the Wi-Fi AP has increased in comparison to the standard Wi-Fi, very distinguishably at higher η , which is clearly a result of increase in the DL opportunity and Successful DL opportunity. The decrease in throughput with η is unambiguous—due to the increased LTE-U interference duration.

Fig. 9 shows how the UL throughput varies with the proposed scheme and standard Wi-Fi. Clearly, the very high UL throughput—in standard Wi-Fi—is because the only user not affected by LTE-U is the non-victim user, and is able to send its data too frequently. Now, with the proposed scheme, this perquisite enjoyed by the non-victim user was moderated. An expectation regarding DL throughput would be that it should be less than the UL (half in the above scenario), which is the case at very low duty cycle, but, as the duty cycle increases, this difference decreases. The decrease, in the

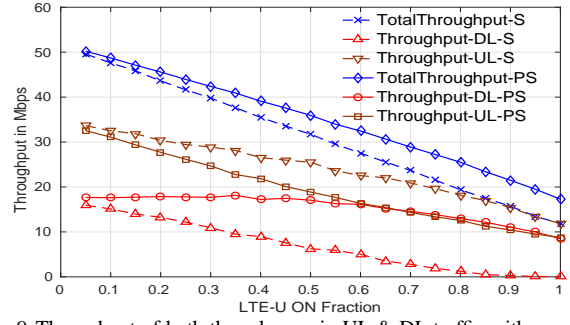


Fig. 9. Throughput of both the schemes in UL & DL traffic with varying η .

considered scenario, can be attributed to the fact that CFP allows equal UL and DL opportunities, during the LTE-U OFF period and during the LTE-U ON period, the proposed scheme prevents Wi-Fi AP from degrading its performance and hence allows it to equally compete with the non-victim user for the channel. Increase in η , further advocates both the above causes. Nonetheless, the total throughput of the Wi-Fi network with the proposed scheme increased by 18%, when averaged over η with a maximum value of 45.5% (at $\eta = 1$), compared to standard Wi-Fi, for the considered scenario.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we focused on improving the performance of Wi-Fi network in the presence of LTE-U network. We have observed that the performance of Wi-Fi, depending on the interference from LTE-U eNB, can degrade to a large extent. We found that, in cases when LTE-U transmissions partially affect Wi-Fi network, not only the fairness among Wi-Fi users is compromised, but also the Wi-Fi AP's throughput is affected. To address this issue, we proposed a scheme based on PCF, which can be easily adopted by Wi-Fi, to ensure fairness among its users and to improve the performance of Wi-Fi AP. The efficacy of the scheme was proved by sufficient analysis and simulation experiments. As a part of future work, we plan to evaluate the performance of multi - LTE-U and multi - Wi-Fi scenario while employing the proposed scheme.

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